Testing Newtonian gravity in the low acceleration regime with globular clusters: the case of ω Centauri revisited.

Riccardo Scarpa[1] and Renato Falomo[2]

[1] Instituto de astrofísica de canarias, c/via Lactea s/n, San Cristobal de la Laguna 38205, Spain
[2] INAF, Osservatorio astronomico di Padova, vicolo Osservatorio 5, Padova, Italy

June 24, 2010

ABSTRACT

Context. Stellar kinematics in the external regions of globular clusters can be used to probe the validity of Newton's law in the low acceleration regimes without the complication of non-baryonic dark matter. Indeed, in contrast with what happens when studying galaxies, in globular clusters a systematic deviation of the velocity dispersion profile from the expected Keplerian falloff would provide indication of a breakdown of Newtonian dynamics rather than the existence of dark matter.

Aims. We perform a detailed analysis of the velocity dispersion in the globular cluster ω Centauri in order to investigate whether it does decrease monotonically with distance as recently claimed by Sollima et al. (2009), or whether it converges toward a constant value as claimed by Scarpa Marconi and Gilmozzi (2003B).

Methods. We combine measurements from these two works to almost double the data available at large radii, in this way obtaining an improved determination of the velocity dispersion profile in the low acceleration regime.

Results. We found the inner region of ω Centauri is clearly rotating, while the rotational velocity tend to vanish, and is consistent with no rotation at all, in the external regions. The cluster velocity dispersion at large radii from the center is found to be sensibly constant.

Conclusions. The main conclusion of this work is that strong similarities are emerging between globular clusters and elliptical galaxies, for in both classes of objects the velocity dispersion tends to remain constant at large radii. In the case of galaxies, this is ascribed to the presence of a massive halo of dark matter, something physically unlikely in the case of globular clusters. Such similarity, if confirmed, is best explained by a breakdown of Newtonian dynamics below a critical acceleration.

Key words. Gravity – Globular cluster – star dynamics

1. Introduction

A fundamental aspect of our knowledge of the Universe concerns the existence of non-baryonic dark matter (DM), believed to represents about 20% of the total energy budget of the Universe. Signatures of DM are found in galaxies and cluster of galaxies due to its dynamical effects and gravitational lensing. While DM appears in wildly variable quantities and distributions among different types of objects, it appears to exhibit systematic (but not yet understood) behaviours (c.f., recent findings by Gentile et al. 2009 and by Donato et al. 2009). The most remarkable (e.g., Binney 2004) being that DM is needed to reconcile the observations with the expectations of Newtonian dynamics when and only when the acceleration of gravity goes below a *critical* value, $a_0 \sim 1.2 \times 10^{-8}$ cm s^{-2} (Begeman et al. 1991).

This fact led to suggest that Newtonian dynamic might not be applicable below this acceleration and the most successful proposal of this type, known as MOND (Milgrom 1983), nicely explains the rotation curves of spiral galaxies and many

Send offprint requests to: R. Scarpa; riccardo.scarpa@gtc.iac.es

other dynamical properties of galaxies without the needs for DM (McGaugh & de Block 1998; Mortlock & Turner 2001; see Sanders & McGaugh 2002 for a review). Such an hypothesis, however, has so many serious consequences for the standard physics (e.g. Milgrom 2009 for a review), that as many test as possible should be carried out to verify it. Experiments can be made in the laboratory or studying astrophysical systems where DM is absent. A first pioneering study along this line focused on the dynamics of the external regions of globular clusters, the largest virialized structures that do not contain significant amount of dark matter. Measurement of the velocity dispersion in the outskirt of ω Centauri (Scarpa, Marconi and Gilmozzi 2003A,B), showed a clear flattening of the velocity dispersion profile starting at the radius where the cluster's internal acceleration of gravity is $\sim a_0$, with no evidence of the expected Keplerian falloff. The very same behaviour observed in elliptical galaxies and explained invoking the presence of large amounts of dark matter. This result was then extended to other 6 globular clusters (Scarpa, Marconi, and Gilmozzi 2003 A,B; Scarpa, Marconi, and Gilmozzi 2004 A,B; Scarpa et al. 2007 A,B; Scarpa et al.
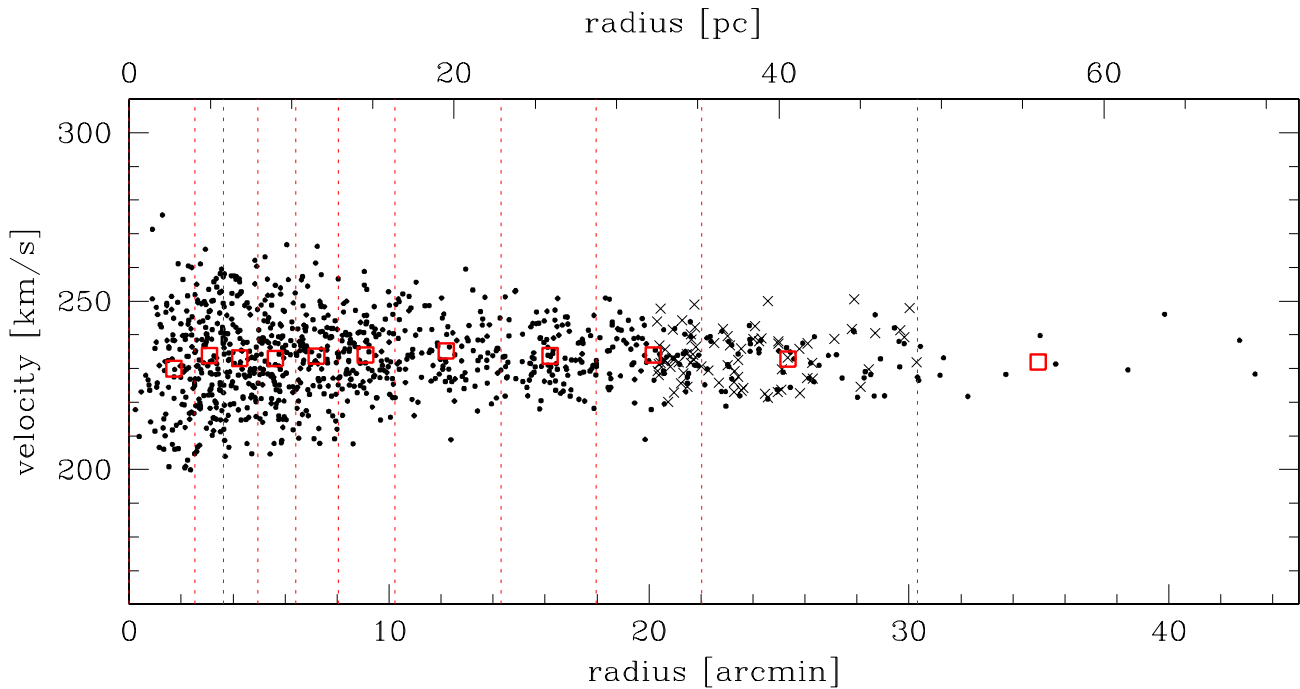
Fig. 1. The distribution of radial velocities from Sollima et al. 2009 (points) as a function of distance from cluster center. The sample of Scarpa, Marconi & Gilmozzi 2003B (crosses), limited to the region $20 < R < 30$ arcmin, almost double the number of points in the region where $a < a_0$. The vertical (dotted) lines give the limits of bins containing 100 points each (beside the last one that contain only 13 points). The average radial velocity within each bin (large open squares) is very stable with no indication of peculiar trends. The uncertainty on the average is smaller than the size of the symbols.

2010), showing the behaviour seen in ω Cen is not a peculiar property of this cluster.

Given the relevance of this result, the dynamics of ω Cen was recently carefully reconsidered by Sollima et al. (2009, S09 hereafter). Based on the analysis of a new large dataset of radial velocities measurements, it was claimed that the velocity dispersion decreases monotonically with radius, in agreement with Newtonian prediction, and in clear contrast with the claim by Scarpa Marconi and Gilmozzi (2003B; SMG hereafter). We reconsider here the data presented by S09. The reanalysis is done joining both the S09 and SMG radial velocities data to create a larger sample. In both works, the selection criteria for cluster members identification was basically the same (a selection based on position in the color magnitude diagram combined with a cut in radial velocity), ensuring that the whole dataset is homogeneous.

Table 1. ω Centauri (NGC 5139) basic properties

RA, DEC (2000)	13:26:45.76, -47:28:42.8	Coordinates of cluster center
L,B	309.10 14.97	Galactic coordinates
R_{sun}	5.5 kpc	Distance from sun
R_{MW}	6.4 kpc	Distance from Milky Way center
M_V	−10.29	Total V band magnitude
Mass/M$\odot$	1.1×10^6	From luminosity assuming M/L$_V$=1
r_e	4.8 arcmin or 7.7 pc	Half light radius
r_t	45 arcmin or 72 pc	Tidal radius
Scale factor	1.60	pc/arcmin

Coordinates are from van de Ven 2006. The exact cluster center used in S09 is 13:26:46.5, -47:28:41.1, Sollima private communication. This minimal difference has no effects on our analysis.

2. Radial velocity measurements for ω Centauri

Located at 6.4 kpc from the galactic center (Harris 1996), ω Cen is the most massive and luminous globular cluster of the Milky Way. It is sufficiently massive to contain more than one stellar population, as indicated by helium abundance variation (Norris 2004; Piotto et al. 2005) and its peculiar position in the size-luminosity plane (Mackey and van der Bergh 2005). It has been also argued that ω Cen could be not a genuine globular cluster but the nuclear remnant of a dwarf galaxy that merged in the past with the Milky Way (e.g., Bellazzini et al. 2008).

Among the earliest dynamical studies of ω Cen relevant to this work, Meylan & Mayor (1986) discussed the radial velocities of 318 cluster members, covering the cluster up to 22 arcmin from the center. Comparing these data to the velocity dispersion derived from proper motion data for several thousands stars (van Leeuwen et al. 2000), it was possible to demonstrate (Scarpa, Marconi & Gilmozzi 2003B) that the velocity ellipsoid is isotropic. A very important result for our purposes, because at large radii only the velocity dispersion along the line of sight can be measured.

Assuming for the cluster a total absolute magnitude of $M_V = -10.29$, distance of 5.5 kpc [1], and mass-to-light ratio M/L=1 in solar units, the acceleration is a_0 at $r_0 \sim 22.3$ arcmin. Thus to extend the results presented by Meylan & Mayor (1986) to radii where the acceleration goes below a_0, SMG obtained radial velocity measurements for 75 cluster members in

---

[1] For consistency we use here a distance of 5.5 kpc as in S09, while in SMG an older value of 5.1 kpc (van Leeuwen et al. 2000) was used.
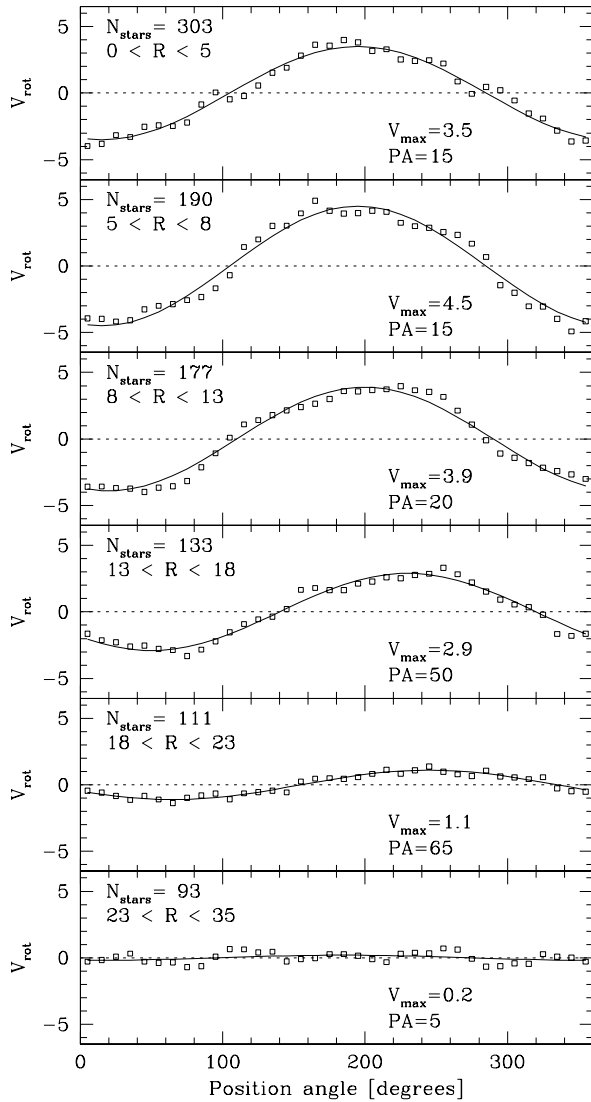
Fig. 2. Rotation (in km/s) of ω Cen in 6 annular regions at increasing distance from the center. The number of stars in each region and the radial distance limits (in arcmin) are shown. The formal value of the maximum velocity, V_{max}, and the position angle, are derived from the best sinusoidal fit to the data (solid line). V_{max} is given in km/s and the position angle in degrees from North toward East.

the region $20 < r < 30$ arcmin. The full list of radial velocities obtained by SMG was not published at that time, thus it is given in Table 2. Details on the observations and analysis of individual measurements are reported in SMG. The work by SMG, while confirming the results by Meylan and Mayor in the region of overlap, showed that the velocity dispersion did not decrease with distance beyond $r \sim 20$ arcmin.

A comprehensive study of this cluster was then presented in van de Ven 2006, discussing both proper motions and radial velocities. The data, however, did cover the cluster only up to 20 arcmin from the center. The velocity dispersion profile was found fully consistent with earlier determinations.

In S09 radial velocities measurements for 946 cluster members, of which 628 originally presented by Pancino et al. 2007, probing the cluster up to $r \sim 45$ arcmin from the center were discussed. The sample included 98 data points in the $20 < r < 45$ arcmin region (Fig. 1), comparable to the number of measurements of SMG. Sollima and collaborators found the velocity dispersion to be decreasing up to ~ 26 arcmin from the center reaching a minimum of 5.2 km/s. Outward, at 32 arcmin, they measured a dispersion of 7 km/s. They regarded this increase "more compatible with the onset of tidal heating that with the effects of MOND or DM", and went on with the conclusion that the velocity dispersion in ω Cen is fully compatible with Newtonian dynamics.

3. The rotation of ω Centauri

ω Cen is one of the most flattened globular clusters known, suggesting a significant rotation component. Before discussing the velocity dispersion, it is therefore important to quantify the fraction of the total energy budget of ω Cen that goes into ordered motion. Clear evidence of rotation in the inner regions of the cluster was found by Meylan and Mayor (1986). More recently Pancino et al. (2007) using a fraction of the S09 sample, measured a maximum rotation of 6.8 km/s between 6 to 8 arcmin from the center. Using the large SMG + S09 combined samples, we evaluated the amount of rotation in 6 regions at increasing distance from the center. In each region we halved the cluster by position angle and compute the mean radial velocity of each half. The difference of these two velocities correspond to twice the rotational velocity. This procedure was applied with steps of 10 degrees in position angle (Fig. 2).

The center of the cluster is clearly rotating. In the two innermost bins the formal value of the maximum rotation velocity is 4.5 km/s, somewhat lower than quoted by Pancino et al. (2007), with rotation axis position angle of 15 degrees (from North toward East). The rotational velocity starts decreasing at $r \sim 10$ arcmin, also showing indication of a possible drift of the rotation axis. In the two most external annulus, the rotational velocity is very small, being consistent with no rotation at all in the outer most bin.

In all six regions, the rotational velocity is significantly smaller than the velocity dispersion (see next section), indicating that the amount of energy stored into ordered rotational motion is negligible compared to the one of the chaotic motion. Thus, at large radii the velocity dispersion should closely follow a typical Keplerian falloff (unless external effects modify it).

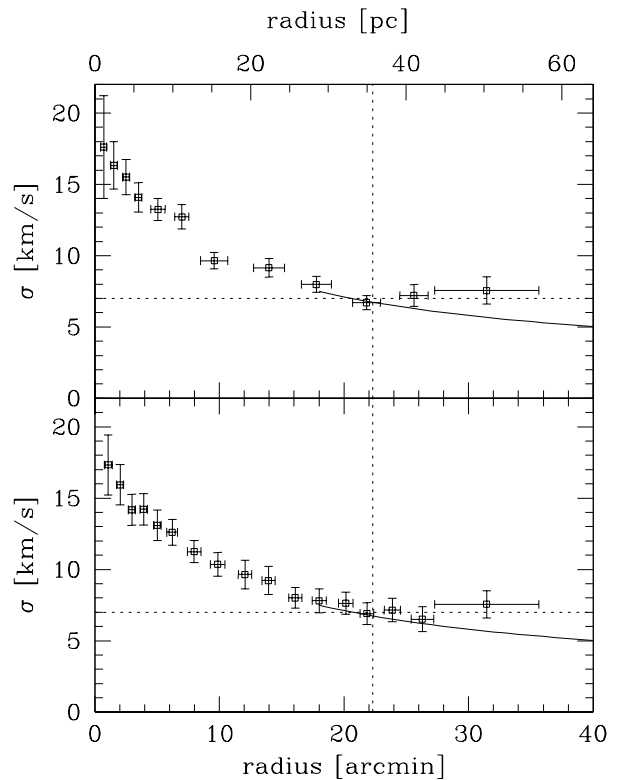## 4. The velocity dispersion profile of ω Cen.

It is well known that binning of sparse and non homogeneously distributed data can produce artificial/spurious trends in binned plots. A bin independent method of constraining the velocity dispersion is shown in Fig. 3, where we plot on top of each other 125 velocity dispersion profiles, each one obtained with a different binning.

To create these profiles, we first sorted the data according to increasing distance from the cluster center. Then we con-
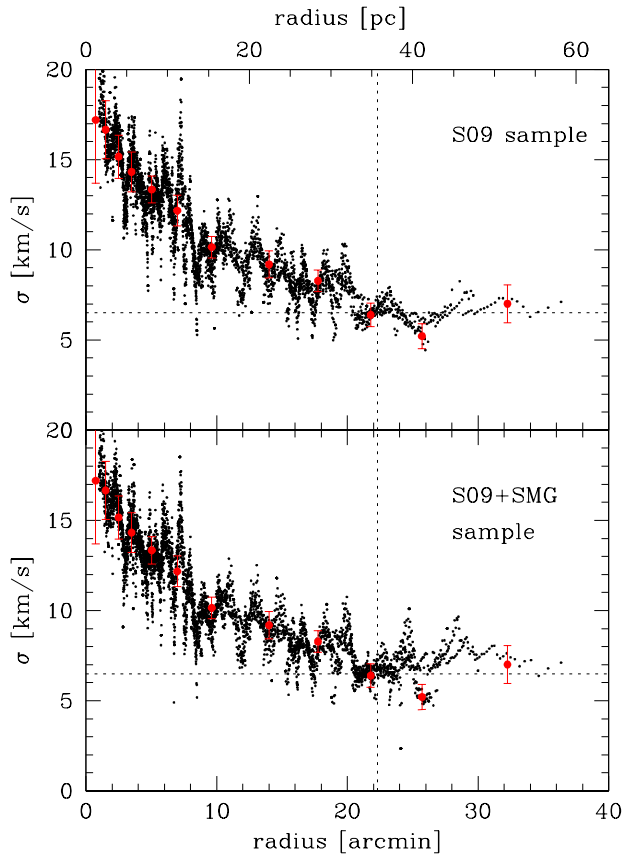
Fig. 3. Plot of 125 velocity dispersion profiles, each one obtained with a different binning of the data from the S09 sample alone (upper panel), or the combined S09+SMG sample (lower panel). The envelope of all these profiles, rather than the singular points, shows the flattening of the profile beyond $r \sim 20$ arcmin. The velocity dispersion reported by S09 (red points with error bars) nicely fall close to the center of the envelope. However, the value of $\sigma = 5.2$ km/s at $r = 25.7$ arcmin is not representative of the data, being in both cases at the very bottom of the envelope. The vertical line gives the MOND radius, while the horizontal one is only meant to highlight the flattening of the dispersion profile.

structed binned data starting from point number 10, 20, 30, 40, and 50, disregarding the innermost points that are irrelevant for our purposes. The number of points per bin, constant for each profile, was varied from a minimum of 10 to a maximum of 50 points, in step of 2. This procedure resulted in 125 different combinations of binned profiles. What is relevant for the description of the velocity dispersion profile is the envelope of all the profiles. While the dispersion varies significantly from point to point, the flattening at large radii is evident, both when using data from the S09 sample alone, and the S09+SMG combined samples. The values computed by S09 (see their Table 1) are very close to the center of the envelope, but the point at $r = 25.7$ ($\sigma = 5.2$) is clearly not representative of the data, being at the bottom of the envelope. It seems to us S09 made an unfortunate choice of the binning, that resulted in an underestimation of the velocity dispersion in the critical region beyond

Fig. 4. The velocity dispersion profile of ω Cen as obtained considering the combined S09+SMG sample, and two different binning. **Top panel:** Data binned as in S09. **Bottom panel:** Narrower sampling for having one extra bin beyond the MOND radius. Points give the velocity dispersion in km/s and its 1σ uncertainty, while the bars in the x direction give the rms of the data in the bin. The vertical dotted line indicates the MOND radius, where the acceleration is a_0. The horizontal line is not a fit to the data, it is only meant to highlight the flattening of the dispersion profile. The solid line show a Keplerian fall off. Note that all these data points fall well within the cluster tidal radius (45 armnin).

22 arcmin. It turns out therefore, that both the S09 and the combined S09+SMG data exhibit a clear flattening (at $\sigma \sim 7$ km/s) of the velocity dispersion profile in ω Cen at large radii ($r > 20$ arcmin).

We present in Fig. 4 the velocity dispersion obtained binning the combined S09+SMG sample with the S09 original binning, and with a narrower binning that better samples the profile (see Tab. 3). The expected Keplerian fall off is also shown. This was computed assuming all the cluster mass is contained within the MOND radius, an assumption justified by the fact that 95% of the cluster total luminosity is contained within a radius as small as 17 arcmin (Trager et al. 1995). Although the departure of the velocity dispersion profile from the Keplerian fall off is modest it shows a systematic trend.

5. Discussion

The analysis of the largest available data set of radial velocities of stars in the globular cluster ω Cen, show the veloc-

ity dispersion at large radii from the center remains constant (Fig. 4). There is indeed no indication of the decrease of the velocity dispersion claimed by S09. The flattening starts at $r = 20 \pm 2$ arcmin, where the Newtonian acceleration of gravity is $a = \frac{GM}{r^2} \sim 1.5 \times 10^{-8}$ cm s^{-2} in line with the values measured in the other globular clusters studied as part of this project (Scarpa et al. 2007A, Scarpa et al. 2010). Here G is the gravitational constant and the mass M is computed assuming a mass-to-light ratio M/L=1 in solar units, and a cluster total absolute magnitude of $M_V = -10.29$ (Harris 1996), further assuming all the mass is contained within the MOND radius, an approximation well within the uncertainties of the M/L ratio.

Although, due to the still limited statistics a Keplerian falloff at large radii cannot be ruled out in ω Cen, combining the results for all globular clusters studied so far there is mounting evidence that globular clusters mimic nicely the behaviour of elliptical galaxies (Scarpa et al. 2010).

Whether this implies this is the effect of MOND in a class of objects that do not contain dark matter remains unclear. Indeed, it was argued (Baumgardt, Grebel and Kroupa 2005) that ω Cen is too close to the Milky Way to provide a useful test for MOND. Milgrom (1983) explicitly stated that due to the strong external field of the Milky Way no deviations from a Keplerian fall off should be observed in ω Cen (this is the case for all the other clusters we studied so far).

Alternatively one might assume M/L> 1 so that the acceleration remains above the MOND threshold at all radii probed by the data. For instance Moffat and Toth (2008) using M/L=2.9 obtained in the framework of Newtonian dynamics a reasonable fit of the dispersion profile from SMG. It would be interesting to see whether it is still possible to fit the current data that exhibits an even more marked flattening. We note, however, that the assumptions of M/L significantly larger than 1 is rather controversial, because in the few cases where the present-day mass function of globular clusters has been measured, M/L is found to be even smaller than 1 (De Marchi 1999; Piotto et al. 1997; Andreuzzi et al. 2000).

Irrespectively of which is the correct theoretical interpretation of the flattening of the velocity dispersion profile, we believe a striking similarity between globular clusters and elliptical galaxies is emerging.

References

Andreuzzi, G., Buonanno, R., Fusi Pecci, F., Iannicola, G., & Marconi, G., 2000 A&A 353, 994

Baumgardt H., Grebel E. K., and Kroupa P. 2005, MNRAS 359 L1

Begeman, K. G., Broeils, A.H., and Sanders, R. H. 1991, MNRAS 249, 523

Bellazzini M., Ibata R. A., Chapman S. C. et al. 2008 AJ 136, 1147

Binney J. 2004, in "Dark Matter in Galaxies", ed. S. D. Ryder, D. J. Pisano, M. A. Walker, and K. C. Freeman, IAUS 220, p. 3

Carollo C. M., de Zeeuw P. T., van der Marel R. P., Danziger I. J., and Qian E. E. 1995, ApJ 441, L25

De Marchi, G. 1999, ApJ 117, 303

Donato F., Gentile G., Salucci P., et al. 2009 MNRAS 397, 1169

Gentile G., Famaey B., Zhao H., Salucci P. 2009, Nature 461, 627

Harris, W.E. 1996, AJ, 112, 1487

Mackey A. D., and van den Bergh S. 2005, MNRAS 360, 631

McGaugh, S., & de Block, W. J. G. 1998 ApJ 499, 66

McLaughlin D. E. and Meylan G. 2003, in New Horizons in Globular Cluster Astronomy, ASP Conference Proceedings, Vol. 296, p. 153. Edited by G. Piotto, G. Meylan, S. G. Djorgovski and M. Riello.

Mehlert D., Saglia R. P., Bender R., and Wegner G. 2000, A&AS 141, 449

Meylan G. and Mayor M. 1986, A&A 166, 122

Milgrom, M. 1983, ApJ 270, 365

Milgrom, M. 2009, arXiv 0912.2678

Moffat J. W., and Toth V. T. 2008 ApJ 680, 1158

Mortlock, D. J., & Turner, E. L. 2001 MNRAS 327, 577

Norris J. E. 2004, ApJ 612, L25

Pancino E., Galfo A., Ferraro F. R., Bellazzini M. 2007 ApJ 661, L155

Piotto, G., Cool, A.M., & King, I.R. 1997, AJ 113, 1345

Piotto G., Villanova S., Bedin L. R. et al 2005, ApJ 621, 777

Sanders, R. H., & McGaugh, S. S. 2002, ARA&A 40, 263

Scarpa, R., Marconi, G., & Gilmozzi R. 2003A, in New Horizons in Globular Cluster Astronomy, ASP Conference Proceedings, Vol. 296, p. 151. Edited by G. Piotto, G. Meylan, S. G. Djorgovski and M. Riello.

Scarpa, R., Marconi, G., & Gilmozzi R. 2003B, A&AL 405, 15 [SMG]

Scarpa, R., Marconi, G., & Gilmozzi R. 2004A, IAUS 220, 215

Scarpa, R., Marconi, G., & Gilmozzi R. 2004B, in "Baryons in Dark Matter Halos", Ed. R. Dettmar, U. Klein, P. Salucci. Published by SISSA, Proceedings of Science, http://pos.sissa.it, p.55.1

Scarpa R., Marconi G., Gilmozzi R., and Carraro G. 2007, The Messenger 128, 41.

Scarpa R., Marconi G., Gilmozzi R., and Carraro G. 2007, A&A 462, L9

Scarpa R., Marconi G., Carraro G., Falomo R., and Villanova S. 2010, A&A, submitted

Sollima A., Bellazzini M., Smart R.L., Correnti M., Pancino E., Ferraro F.R., and Romano D. 2009, MNRAS 396, 2183 [S09]

Trager S. C., King I. R., and Djorgovski 1995, AJ, 109, 218

van de Ven G., van den Bosch R. C. E., Verolme E. K., and de Zeeuw P. T. 2006, A&A 445, 513

van Leeuwen F., Le Poole R. S., Reijns R. A., Freeman K. C., and Zeeuw P. T. 2000, A&A 360, 472

Table 2. Heliocentric Radial velocities for ω Centauri members

ID	RA (2000)	DEC (2000)	Velocity [km/s]
00006	13 : 25 : 06.00	−47 : 09 : 21	222.62 ± 0.51
01008	13 : 25 : 14.88	−47 : 09 : 51	222.55 ± 0.87
01009	13 : 25 : 49.67	−47 : 09 : 49	244.38 ± 0.00
02005	13 : 25 : 15.12	−47 : 10 : 18	242.54 ± 0.12
05007	13 : 25 : 37.91	−47 : 11 : 29	230.56 ± 2.44
05008	13 : 25 : 40.93	−47 : 11 : 40	228.03 ± 1.05
06009	13 : 25 : 35.46	−47 : 12 : 00	235.71 ± 0.00
08003	13 : 24 : 16.22	−47 : 13 : 11	239.34 ± 1.07
08004	13 : 24 : 17.07	−47 : 13 : 14	241.36 ± 0.75
10006	13 : 24 : 39.15	−47 : 14 : 00	237.46 ± 1.27
10009	13 : 24 : 58.69	−47 : 14 : 02	227.59 ± 1.13
10010	13 : 25 : 20.30	−47 : 14 : 00	220.13 ± 1.27
13006	13 : 24 : 32.09	−47 : 15 : 31	231.72 ± 0.69
14002	13 : 24 : 38.98	−47 : 15 : 52	223.74 ± 0.54
15007	13 : 25 : 06.38	−47 : 16 : 22	222.83 ± 0.25
16003	13 : 24 : 03.53	−47 : 16 : 48	247.97 ± 0.70
19005	13 : 24 : 12.87	−47 : 17 : 53	224.55 ± 1.91
20006	13 : 24 : 34.17	−47 : 18 : 30	250.01 ± 0.00
22007	13 : 24 : 20.45	−47 : 19 : 35	226.94 ± 0.90
22008	13 : 24 : 59.82	−47 : 19 : 16	229.30 ± 0.00
24011	13 : 24 : 50.82	−47 : 20 : 09	228.63 ± 0.96
25004	13 : 24 : 44.87	−47 : 20 : 45	230.58 ± 0.52
26009	13 : 24 : 47.16	−47 : 21 : 14	224.52 ± 0.01
27008	13 : 24 : 39.61	−47 : 21 : 47	237.51 ± 1.24
28009	13 : 24 : 32.94	−47 : 21 : 53	235.90 ± 0.62
31006	13 : 24 : 30.90	−47 : 23 : 35	232.55 ± 0.00
33006	13 : 24 : 30.77	−47 : 24 : 26	225.94 ± 1.69
34008	13 : 24 : 46.79	−47 : 24 : 48	232.19 ± 0.81
37009	13 : 24 : 38.53	−47 : 26 : 19	234.19 ± 0.23
39013	13 : 24 : 38.58	−47 : 27 : 03	231.71 ± 0.90
42009	13 : 24 : 26.66	−47 : 28 : 19	223.46 ± 1.60
42012	13 : 24 : 41.85	−47 : 28 : 29	232.86 ± 1.11
43002	13 : 24 : 34.11	−47 : 28 : 44	229.36 ± 0.53
45011	13 : 24 : 26.25	−47 : 29 : 38	224.22 ± 0.58
45014	13 : 24 : 37.49	−47 : 30 : 00	248.95 ± 0.47
46003	13 : 24 : 31.06	−47 : 30 : 09	241.79 ± 0.51
48009	13 : 24 : 28.89	−47 : 31 : 06	223.06 ± 0.78
49008	13 : 24 : 38.96	−47 : 31 : 37	238.58 ± 0.83
51005	13 : 24 : 22.05	−47 : 32 : 22	221.38 ± 0.69
57006	13 : 24 : 44.54	−47 : 35 : 06	234.32 ± 0.38
61009	13 : 24 : 38.47	−47 : 36 : 58	239.66 ± 0.47
64010	13 : 24 : 44.13	−47 : 38 : 21	225.80 ± 2.67
72007	13 : 25 : 02.53	−47 : 41 : 51	236.44 ± 1.02
75005	13 : 24 : 39.87	−47 : 43 : 21	235.89 ± 3.84
76015	13 : 25 : 21.21	−47 : 44 : 03	241.52 ± 0.75
77010	13 : 24 : 56.51	−47 : 44 : 28	238.13 ± 0.78
78004	13 : 24 : 14.39	−47 : 45 : 00	231.88 ± 0.76
78008	13 : 24 : 52.57	−47 : 44 : 48	222.95 ± 0.57
79008	13 : 25 : 03.49	−47 : 45 : 27	238.80 ± 1.00
80017	13 : 25 : 36.42	−47 : 45 : 31	231.63 ± 0.75
80019	13 : 25 : 39.47	−47 : 45 : 49	236.88 ± 1.46
82012	13 : 25 : 46.06	−47 : 46 : 45	232.43 ± 0.57
85007	13 : 24 : 46.16	−47 : 48 : 02	250.58 ± 0.37
85014	13 : 25 : 30.54	−47 : 48 : 04	236.89 ± 0.82
85019	13 : 26 : 09.52	−47 : 48 : 06	244.01 ± 0.64
86007	13 : 24 : 53.73	−47 : 48 : 16	238.73 ± 0.80
86010	13 : 25 : 14.92	−47 : 48 : 28	238.07 ± 0.61
86017	13 : 26 : 14.90	−47 : 48 : 27	231.25 ± 1.41
87009	13 : 26 : 28.10	−47 : 48 : 58	247.74 ± 0.64
88022	13 : 26 : 17.91	−47 : 49 : 27	225.56 ± 0.00
88023	13 : 26 : 20.45	−47 : 49 : 13	233.11 ± 0.52
89009	13 : 26 : 16.96	−47 : 49 : 58	242.16 ± 0.53
89014	13 : 26 : 39.70	−47 : 49 : 51	231.79 ± 0.44
90008	13 : 24 : 53.91	−47 : 50 : 24	240.48 ± 0.44
90019	13 : 26 : 30.06	−47 : 50 : 17	232.78 ± 0.49
90020	13 : 26 : 34.47	−47 : 50 : 17	240.16 ± 0.62
91010	13 : 25 : 20.97	−47 : 50 : 34	227.18 ± 2.77
93016	13 : 26 : 36.13	−47 : 51 : 43	230.91 ± 0.67
94011	13 : 25 : 14.21	−47 : 51 : 53	241.77 ± 0.58
94014	13 : 26 : 31.35	−47 : 51 : 55	229.29 ± 0.10
95013	13 : 25 : 58.71	−47 : 52 : 26	237.44 ± 0.53
95015	13 : 26 : 11.78	−47 : 52 : 22	238.97 ± 0.53
96011	13 : 26 : 05.55	−47 : 52 : 55	229.73 ± 0.65
97012	13 : 26 : 06.65	−47 : 53 : 12	233.22 ± 0.00
98012	13 : 25 : 25.27	−47 : 53 : 46	229.82 ± 0.67

Table 3. Radial velocity dispersion for ω Centaury

Bin limits (arcmin)	R (arcmin)	N	Dispersion km/s
0 − 1.5	1.07	34	17.33 ± 2.11
1.5 − 2.5	2.03	63	15.94 ± 1.42
2.5 − 3.5	2.98	86	14.18 ± 1.08
3.5 − 4.5	3.92	83	14.22 ± 1.11
4.5 − 5.5	5.01	75	13.09 ± 1.07
5.5 − 7	6.22	100	12.61 ± 0.89
7 − 9	7.97	104	11.25 ± 0.78
9 − 11	9.87	78	10.35 ± 0.83
11 − 13	12.06	47	9.64 ± 1.00
13 − 15	13.95	44	9.21 ± 0.99
15 − 17	16.09	64	8.01 ± 0.71
17 − 19	18.01	44	7.80 ± 0.84
19 − 21	20.14	50	7.63 ± 0.77
21 − 23	21.85	42	6.90 ± 0.76
23 − 25	23.88	39	7.14 ± 0.82
25 − 28	26.30	28	6.51 ± 0.88
28 − 44	31.46	32	7.56 ± 0.95

Column 2 gives the average radius of the points in the bin.
Column 3 gives the number of stars per bin.